The Impact of Unsteady Aerodynamics on the Loading of Flight Vehicles

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Abstract. *This paper describes the growing use of computational fluid dynamics (CFD) at the Lockheed Martin Aeronautics Company to assess and design for unsteady loads. The experience in development and in use of CFD for unsteady loads is presented in four sections: (1) background and motivation leading to the development of this capability, (2) an overview of the tools and processes utilized in disciplinary and multidisciplinary simulations, (3) a series of application and computational verification studies, and (4) a description of capabilities currently in development.*

1.0 BACKGROUND AND MOTIVATION

Worldwide, the aerospace industry has been consolidating since the 1980's. Simultaneous to the changing culture in industry, new technologies are impacting aerodynamics, structures, and controls interactions (ASCI) in aircraft design and operation. A realized attrition of experience in aircraft design coupled with an accelerating capacity in computational modeling motivated a study to capture knowledge from recent aircraft programs and establish direction for the development of computational technologies. The goal was to minimize costly redesigns and unforeseen flight limitations often discovered after a vehicle is introduced into usage. To address these issues, ASCI technology development was planned through government and industry collaboration under the U.S. Fixed Wing Vehicle Program in the mid 90's.

A historical study of aircraft development and support was initiated to provide a basis for strategic development of computational technologies. The "Identification of Critical Flight Loads" (CFL) program was directed to recommend a path to improve prediction and understanding of critical flight loads. Critical flight loads are those flight loads that are used for structural design and sizing, for component arrangement and placement, and after final design, for the determination of safe flight operational limits. In the CFL program a database of "missed" critical flight loads events was created and populated with information from aircraft manufactured by the legacy companies of Lockheed Martin, Boeing and Northrop Grumman. The Lockheed Martin / Northrop Grumman effort, under Air Force funding, is summarized in two documents. (References 1, 2) This effort was coordinated with the Boeing effort to ensure a consistent and integrated database. (Reference 3) The approach captured historical critical flight loads data where unanticipated structural response and/or damage were observed. The data was characterized in categories: aircraft problems, causes, subcauses, components, and corrective actions. A total of 128 incidences were recorded in the Lockheed Martin / Northrop Grumman surveys. Aircraft surveyed include F-16, F-5E/F, F-14, P-3, S-3A, C-130, and the L-1011. In addition technical information concerning the F-111, EF-111, B-2, and YF-23 was included.

The CFL study identified missed critical flight load occurrences, determined characteristic problem types, and correlated causes, subcauses, and corrective actions for each occurrence. The category of problem types with the largest number of occurrences is "Excessive Static Load." Forty-seven percent of missed flight loads conditions are derived from loads sustained during a maneuver. This high percentage of "Excessive Static Load" occurrences is in the database influenced by the number of F-16 incidences

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recorded. The F-16's high-g performance and relatively simple geometry creates a wide range of load conditions across its performance envelope. For instance, events recorded in the "Excessive Dynamic Load" category include loads due to store ejections, jet wake encounters, and buffeting. High performance aircraft with twin vertical tails have a history of "Excessive Dynamic Load."

A common cause in the various problem types is inadequate loads analysis. This cause arises from misunderstood or misrepresented aerodynamic or inertia data, improper loads analysis methodology, and inaccurate structural flexibility data. Transient maneuver and integrity analysis play an important roll in identifying critical flight loads conditions; so inadequate modeling is a constant concern.

The CFL study also determined that missed conditions can result from incomplete or otherwise deficient loads criteria specifications. Typically, criteria are derived from historical specification documents and are expanded through significant historical test or operational data. Aircraft design demands requirements that incorporate new aircraft technology. Recent studies in Morphing Aircraft Structures have examined such an impact on criteria definition. (Reference 4) Modern use of digital control systems integrate a variety effectors including thrust vectoring. Computerized control may allow aircraft control rates and directions unanticipated by existing design and operation specifications.

Cross correlation studies of the database show that "Inadequate Loads Analysis" is the largest root cause of missed flight loads. Analysis within this cause category indicates that accurate and fully representative aerodynamic data is the dominant need in the problem types recorded. Aerodynamic data is information concerning basic aerodynamic performance ("aircraft stability and control data"), wind tunnel measured data, aerodynamic control surface effectiveness (including aeroelastic effects), and local flow phenomena. In one occurrence, the cause of a missed flight load condition was attributed to "an inability to believe the wind tunnel data." This illustrates a fundamental issue facing industry. Aerodynamic characterization of a

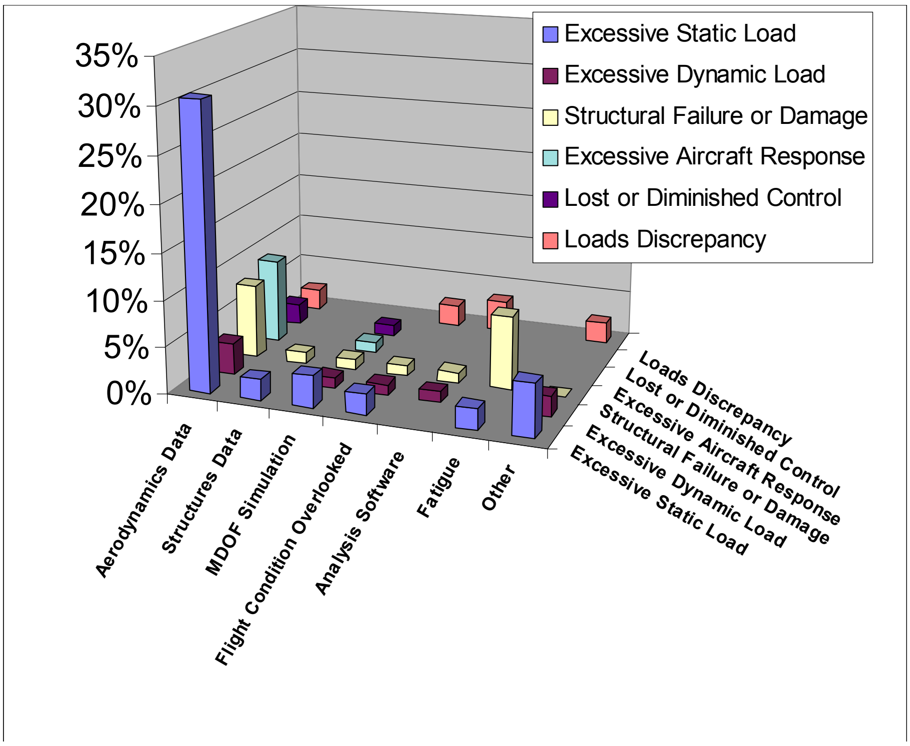

Figure 1. Critical Flight Loads Study Shows Need for Aerodynamic Modeling

flight vehicle requires more than testing, or analysis. To fully comprehend the magnitude of issues in developing critical flight loads requires experience.

Technology programs were recommended to the U.S. Air Force to motivate the development and use of variable fidelity aerodynamics to improve characterization studies including coupling with structures and controls methodologies. In addition, development programs for thermo-vibroacoustics and robust loads methodologies were recommended. The drive to develop these simulation capabilities is based on the expanding cost to develop and certify hardware, and the availing capacity to perform increasingly more complex computational analyses. A statistically significant number of the issues identified were due to the inability to capture and/or include complex aerodynamic flows in multidisciplinary analysis systems. Thus, the ability to intelligently incorporate variable fidelity aerodynamic predictions into simulation packages for maneuver loads, unsteady airloads and aeroservoelastic stability was identified as a critical need.

The key to achieving full use of CFD in predicting steady and unsteady loads is relying on lessons learned in aircraft development, support, and application studies. When coupled in multidisciplinary simulations, the analysis process needs to leverage existing disciplinary expertise via an integrated team within a company. Because of parallel development efforts within each discipline, and the desire to avoid single purpose, specialized versions of each analysis code, a loosely coupled approach is being pursued at Lockheed Martin Aeronautics Company.

This paper traces application developments of CFD in unsteady flows at Lockheed Martin Aeronautics. Beginning with a brief description of tools used for time-accurate CFD and multidisciplinary simulations, the paper covers several applications in design and analysis of flight systems, including conformal fuel tank design to withstand gun blast waves, Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) applications to pod integration and wake analysis, optical interference due to wakes, and flow control, as well as application of experimental and computational approaches towards F-16 and F/A-22 fin buffet. Most recent developments toward a fully time-accurate computational aeroservoelastic maneuver simulation are also presented.

2.0 TOOLS

Lockheed Martin uses many tools for high fidelity aerodynamic and aeroelastic analysis. Splitflow, an unstructured, Cartesian, Euler/Navier-Stokes solver, is used for time accurate analysis of aerodynamic loads on complex geometry. (Reference 7) For flows dominated by viscous features, Falcon, an arbitrary topology, polyhedral, Euler/Navier-Stokes solver is used. Both codes have been integrated with the MultiDisciplinary Computing Environment (MDICE™) to facilitate the execution of multidisciplinary analyses. (Reference 8) Structural responses are determined from a choice of three customized linear solvers; (1) a modal based approach, (2) a direct flexibility matrix approach, (3) or a direct linking with MSC.Nastran™.

The Falcon code offers time-accurate viscous solutions through a variety of modeling features. Included in Falcon are multi-block and overset schemes. Navier Stokes solutions are derived from turbulence models or wall functions. The solver is capable of flows from very low to high supersonic Mach numbers. Unsteady solutions include time-varying boundary conditions.

Splitflow's (Figure 2) Cartesian grid approach enables rapid and dependable Euler solutions for complex geometry. The unstructured Cartesian grid is automatically generated using recursive cell subdivision. A prismatic layer can also be added near walls for resolution of boundary layers for Navier-Stokes analyses. A secondary system, using wall functions is also available.

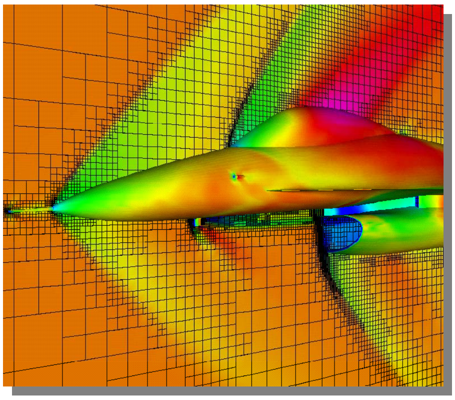

Figure 2: A Splitflow Solution Demonstrating Automated and Adaptive Gridding

Splitflow's automated grid generation requires the triangulated definition of surface geometry only, and uses a recursive cell division algorithm to provide sufficient resolution near defined boundaries. Subsets of the triangulated surface can be used to define system level components (e.g., leading edge flap), and facilitate rapid geometry changes. These subsets simplify the association of CFD components with their counterparts in the structures and controls domains. Solution refinement through grid adaptation is accomplished by gradient analysis of selected flow quantities and recursive cell division. Falcon provides a similar capability for polyhedral, arbitrary topology (mixed-type) meshes, though Falcon is traditionally used for viscous and thermal problems.

In the late 1990's a desire to rapidly capture aeroelastic phenomena with full airframe geometry motivated the integration of Lockheed Martin's Splitflow into a loosely coupled aeroelastic analysis method. Using the CFD Research Corporation' Multidisciplinary Computing Environment, MDICE, Splitflow was quickly coupled with structural solvers for linear static and dynamic solutions (References 9, 10).

Use of Splitflow represents a unique approach that updates the fluid-structure interaction solution at each aeroelastic iteration by re-cutting the Cartesian grid. The grid remains stationary while the geometric definition (i.e., Splitflow facets) passes through the flow field. The MDICE conservative and consistent interpolation methods are used to integrate the pressure distribution over aeroelastic boundaries and interpolate the resulting forces to the structural mesh, and then update the Splitflow facets to match the resulting structural deformation. The grid is de-refined and refined around the new position at each iteration using Splitflow's Cartesian grid cell cutting approach (see Figure 3).

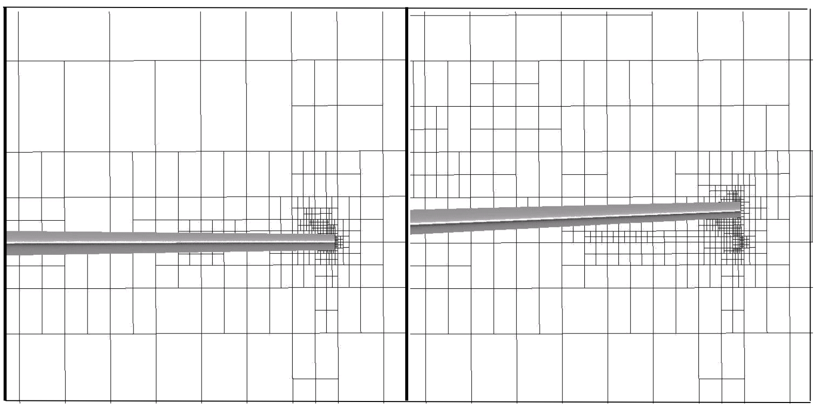

Figure 3: Aeroelastic Solution Process Exploits Cartesian Grid Method of Splitflow

For static aeroelastic solutions, a variable time-step approach is employed by Splitflow, and aerodynamic solution convergence is achieved between the transfer of forces and deflections. This process is repeated until a system level convergence has been achieved, which is typically determined by monitoring a combination of deflection and integrated forces and moments. Dynamic aeroelastic solutions are pursued in much the same way, though forces and deflections are exchanged every-iteration, a single time-step is used for both the aerodynamic and structural solvers. Surface velocity terms are accounted for by Splitflow, and are obtained by finite differencing the interpolated deflections.

All disciplinary analyses are initiated from within MDICE. Each analysis loads grid and restart information and then, releases execution control to MDICE. Once each module is placed in a wait mode, the simulation is run through the scripting language, which is executed through the MDICE GUI. The first command usually issued to each module creates an interface object within MDICE. An interface object stores pointers to the grid and variable information that resides directly in the analysis module's memory. Following, MDICE assembles the interface objects, or performs calculations necessary for the interpolation of quantities between the disciplinary grids.

A number of building block analyses have been performed, including correlation with static aeroelastic and flutter wind tunnel test data and correlation with F-16 flight test data. Figure 4 illustrates the static aeroelastic correlation with a 1979 test from the U.S. Air Force Validation of Aeroelastic Tailoring (VAT) program, while Figure 5 illustrates analysis of an F-16 critical flight loads measured in a 9g turn. The correlation is excellent. In both cases, the wing is washing out and allowing the flow to remain steady and attached. For the rigid configuration, the flow is separated and unsteady. In figure 5, a typical method for computing loads is plotted. This method utilizes "flexibilized" rigid wind tunnel data in which linear aeroelastic solutions about locally nonlinear aerodynamic data points connote "flexibilized" data.

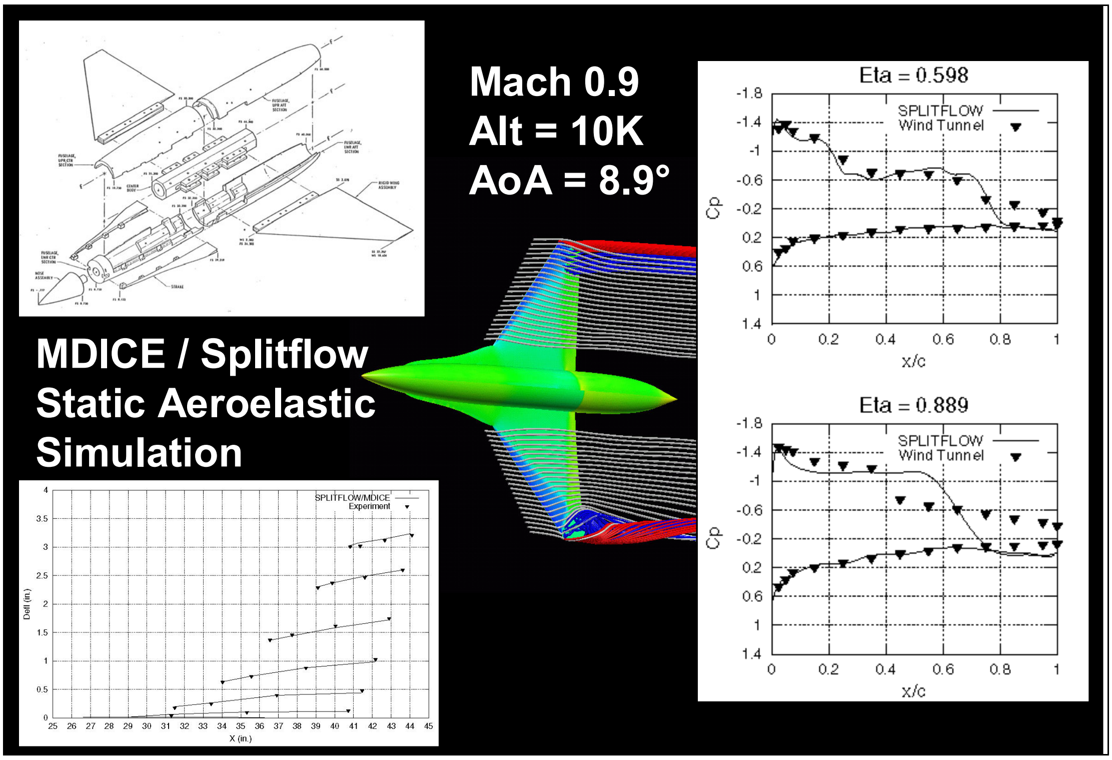

Figure 4: Aeroelastic Tailoring Static Aeroelastic Wind Tunnel Test Correlation

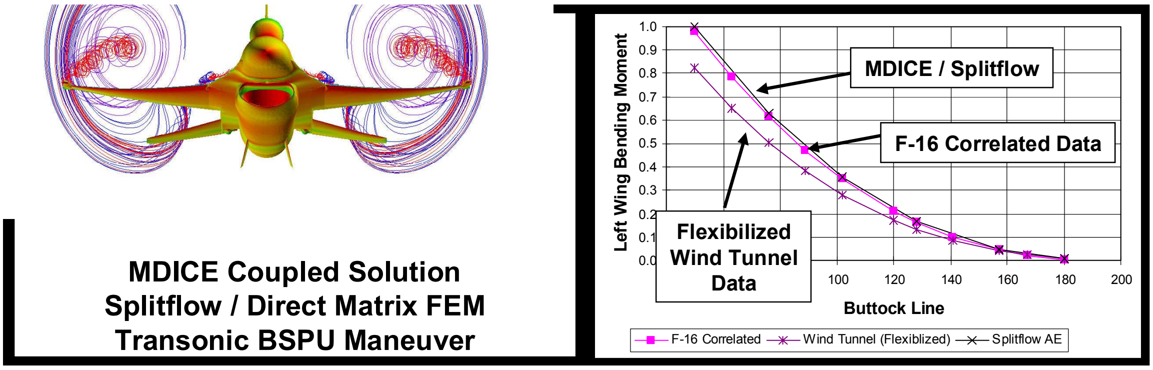

Figure 5: Building Block Correlation with Flight Data

This computational aeroelastic analysis capability has since been used in F-16 development programs where the impact of heavy stores has been addressed from a flight control law development perspective. Figure 6 illustrates a critical store condition analyzed. In this case, the bomb rack acts like a ramp moving the center of pressure forward, impacting the basic flexible stability derivatives. Other aircraft programs are being supported with this approach, and viscous solutions have been acquired on selected basis.

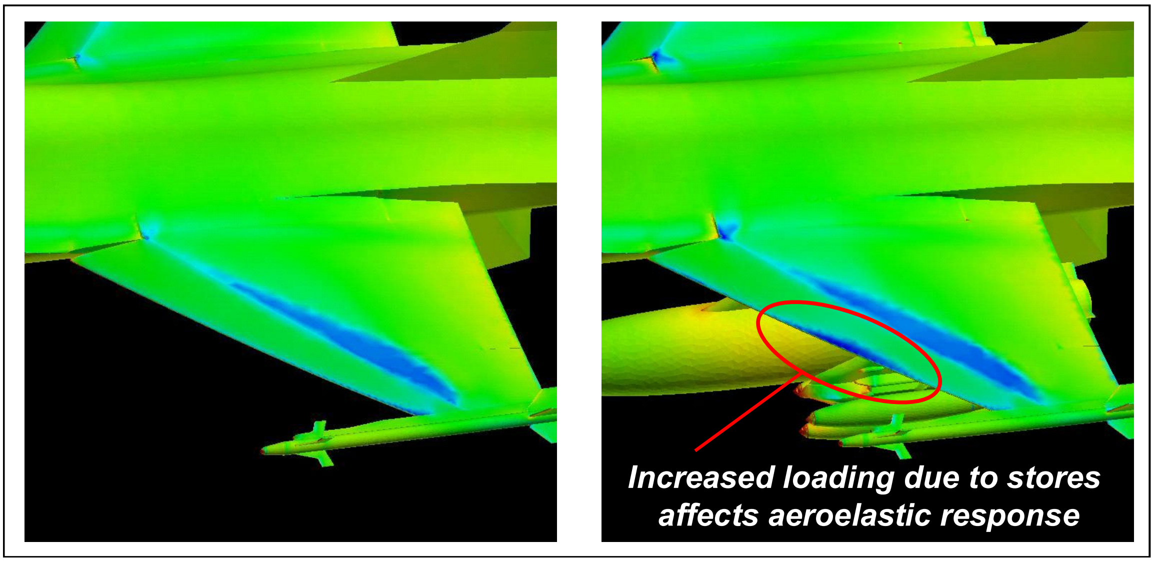

Figure 6: Capture of Complex Geometry in High Fidelity Computational Aeroelastic Solution

A building block approach is also being executed for the time-accurate unsteady capability. Utilizing the flutter database from the VAT program, an Euler based flutter boundary has been computed. The VAT wash-in aeroelastically tailored configuration was tested at the NASA LaRC Transonic Dynamics Tunnel in 1980. (Reference 11) Flutter boundaries have been acquired through iterating solutions on dynamic pressure. Much care was taken to assure that the structural stiffness and mass properties are properly modeled. Viscous solutions are being pursued in 2005. Also planned for 2005 is the initiation of F-16 limit cycle oscillation analysis.

While the basic building blocks for an integrated computational aeroelastic tool have been assembled, CFD development and application studies in unsteady flow analysis have advanced the practice of computational simulation in design. The following section provides recent examples.

3.0 APPLICATIONS

3.1 Simulation of Gun Blast Loads for Conformal Tank Design

In the recent F-16 conformal fuel tank re-design effort time accurate CFD analysis was incorportated to develop unsteady flight loads due to gun blast waves. (Reference 12) This study used high fidelity analysis verified through live-fire ground testing; demonstrating the significant improvement this technology provides in the design process. Previous efforts required multiple iterations and expensive testing.

Conformal fuel tanks were added to the F-16 Block 60 Aircraft in order to increase its range, mission, and store capabilities without impacting its flight capabilities. (Reference 13) As the design of the tank evolved, the forward portion of the tank began to cover the gun port. Figure 7 shows the initial and final CFT Tank configuration. This study was focused on reshaping this forward portion of the tank to allow the gun to fire while reducing dynamic pressure loading on the tank surface due to gun blast waves. Because the actual tank surfaces would be in close proximity to the muzzle of the F-16's M61A1 cannon, a 6 barrel gattling gun which fires 20mm shells at the rate of 100 rounds per second, a critical requirement of the predictive methodology was accurate prediction of rapidly varying pressure on complicated geometry. Additionally, this method needed to account for the injection of high pressure, high temperature gas in to regions of stagnant flow.

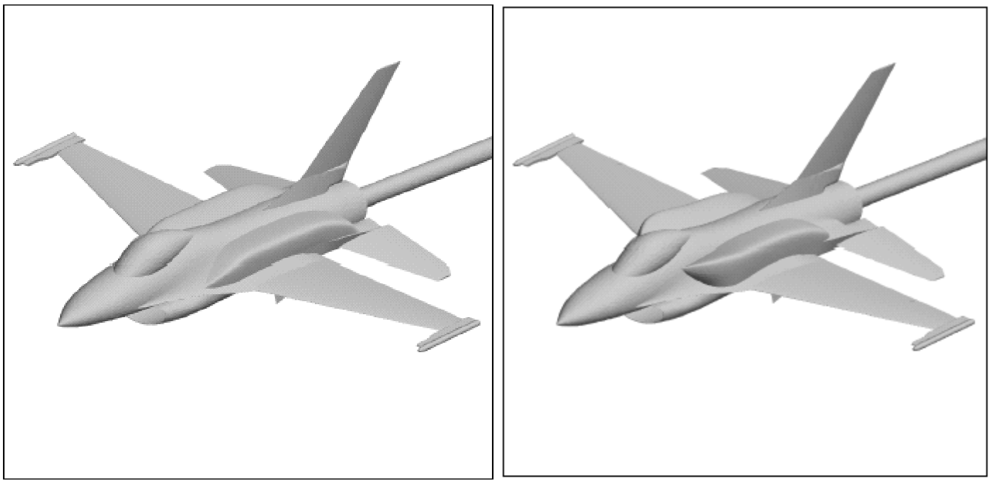

Figure 7. A Comparison of the Initial and Final CFT Configuration

The tool chosen for this study was Splitflow. Because the dominant flowfield feature for this problem, a pressure wave, was kinetic in nature, an Euler analysis was deemed suitable. Additionally, viscous effects would tend to dissipate the propagation of the pressure wave, thus making an Euler analysis conservative in prediction of pressure loads. A reduced domain model of the region near the tank/muzzle interface region was developed in order to minimize the computational cost of running a large number of analysis cases. The blast wave was simulated by a time dependent, total pressure, total temperature (T_0, P_0) boundary condition applied to the surface modeling the gun muzzle. The solver was run in a time accurate mode using a time step of 1μs to preserve second order accuracy and to keep the solution stable. Figure 8 depicts a blast wave propagating through the reduced domain used to model this problem.

Because of the myriad of factors involved with the firing of the M61A1, it would be very difficult to calculate the appropriate values for the total pressure and total temperature boundary condition from first principles, therefore an empirical approach was taken. In order to calibrate the total temperature, total

pressure boundary condition test, data from the F-22 gun door test was used. The F-22, which uses the same cannon as the F-16, makes use of an actuated door which covers the gun port when the cannon is not in use. (Reference 14) Though available data was limited, pressure taps had been placed on this door for live fire ground testing. A door, similar in size and shape, was added to the F-16 reduced model domain, and the total pressure and temperature values were modified until representative pressures were obtained on the door surface.

As the CFT tank design further progressed, aided by a design of experiments method, a family of tank shapes emerged which met the established performance and operational requirements. (Reference 15) Each of these tanks shapes were modeled in the reduced domain, and an analysis was performed. Static pressures, iso-surfaces of static pressure, and surface static temperatures were monitored to assess the impact of the blast wave on each tank design. Due to the complex evolution of the blast wave as it emerges from the cannon muzzle and reflects off of the various surfaces, visual interpretation of the solutions played a large part in assessing the susceptibility of each design to the effects of the blast wave. Movies of the propagation of the blast wave were generated by interrogating sequential solution datasets using FIELDVIEW**.** (Reference 16) Using this data, the design of the tank eventually evolved so that the nose of the tank moved away from the muzzle, allowing the blast wave to dissipate, rather than reflecting the blast wave towards the aircraft.

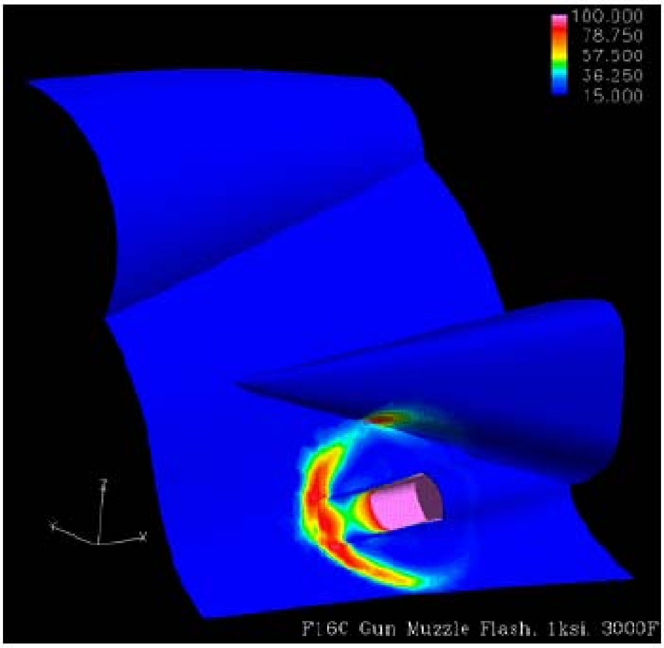

Figure 8. A Reduced Domain Model of Region Near the Tank/Muzzle Interface Showing the Propagation of a Gun Blast Wave

Live fire testing was required to validate the predictions generated by this study. A stainless steel model representing the selected tank design was constructed and equipped with an array of twelve high response pressure taps, strain gauges, accelerometers, and temperature probe. The tank was mounted to a retired airframe used for live fire tests at the Gun Test Lab at the LM Aero Fort Worth Facilities. Approximately 2000 rounds in 50 to 100 round bursts were fired, and recorded with high speed video. The measured pressure response correlated reasonably well with the predicted response. Data traces showed that minimum and maximum peaks were predicted as well as the time between peaks. Additionally, the slopes of the transient data also correlated reasonably well.

3.2 Viscous, Turbulent Applications

LM Aero has been applying Navier-Stokes CFD tools equipped with Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) turbulence models to a wide variety of unsteady aerodynamic problems, including analysis of pod wakes, wake effects on pod optics, weapon bay acoustics, and prediction of pulsed jet injector induced thrust vectoring.

The wakes of aircraft stores can have a major impact on the structural integrity of airframes due to the high acoustic loadings they can generate. Sonic fatigue can lead to catastrophic structural failure, therefore prediction and control of these wakes can provide great benefit to aircraft design and operation. Numerical and physical simulations endeavoring to characterize the nature of these flows have been performed with the goal of gaining an understanding that can be applied towards the design of flow control systems for the mitigation of wake effects. Navier Stokes simulations using Falcon with both RANS and LES turbulence models, water tunnel tests utilizing hydrogen bubble visualization and Particle Image Velocimetry (PIV), and low speed wind tunnel tests were performed on a generic store. It was determined that the vortex shedding in the wake was periodic, with the dominate mode scaling with the Strouhal number. Good correlation was obtained between numerical and experimental methods for both steady and unsteady wake pressure measurements and Strouhal scaling. (Reference 17)

The integration of a high energy laser (HEL) system onto a flight vehicle requires strong consideration of the surrounding flowfield due to acoustical excitation placed on the structure and density variations existing in turbulent wakes that affect optical performance. RANS/LES-based unsteady CFD analyses were performed using Falcon on a fuselage/turret configuration. The predicted unsteady density fields were used to perform an aero-optical analysis of the laser beam path originating from the turret. Figure 9 illustrates these density fields as well as several of the beam paths used to evaluate this configuration. Various parameters describing the distortion of the beam as it propagates from the turret showed that the flowfield would have a significant impact on the integration of a turret based HEL system, and detailed studies such as this would be required for similar integration efforts. (Reference 18)

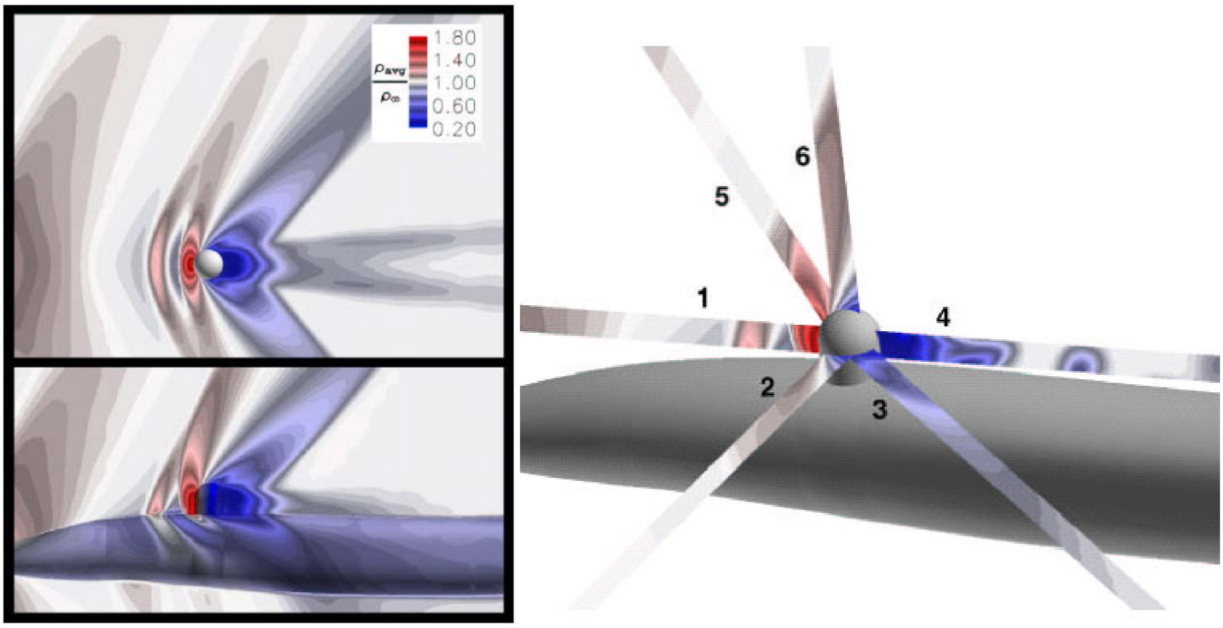

Figure 9. Instantaneous Density Contours on a Pod/Fuselage Configuration and Beam Path Definitions

Euler/LES methods have also been applied to the analysis of weapon bay acoustics, with the additional consideration of the effects of pulsed injection near the leading edge of the cavity to control acoustic levels. Weapon bays experience high acoustic loading due to the interaction of the separated shear layer with reflected acoustic waves. These loads are a major consideration in the structural design of the bay and can limit the store capabilities of the flight vehicle. Recent studies (References 19-23) have shown the value of various methods of pulsed injection, therefore the goal was to demonstrate a prediction capability to facilitate the design of such systems. Analyses were performed on the simple rectangular cavity, with slots at the leading edge to accommodate pulsed injection, as used in Reference 21. Results showed that a qualitative understanding of cavity fluid dynamics can be achieved with CFD. Guidelines were also developed which illustrated the applicability of various levels of CFD solver fidelity for different flow types.

Work has also been done in the area of predicting the effectiveness of flow control systems in improving the performance of propulsion systems. Time accurate RANS and LES simulations have been used to investigate the performance of pulsed injection and ejection techniques for flow control of structurally fixed propulsion systems. The pulsed flow creates a blockage within the nozzle, shown in Figure 10, creating an oblique shock and modifying the velocity vector of the exiting flow, in a manner similar to mechanical actuation. This pulsed jet approach has a significant weight savings benefit, and is therefore of particular interest. This study focused on varying injector conditions such as pulse frequency, injector diameter, and injection speed and measuring their effect on the resulting injector jet structure, penetration of the jet into the crossflow, diameter, trajectory, and blockage ability. CFD analyses predicted that the pulsed jet creates a well organized vortex ring structure with improved penetration into the cross flow and larger diameter over steady injection. (Reference 24)

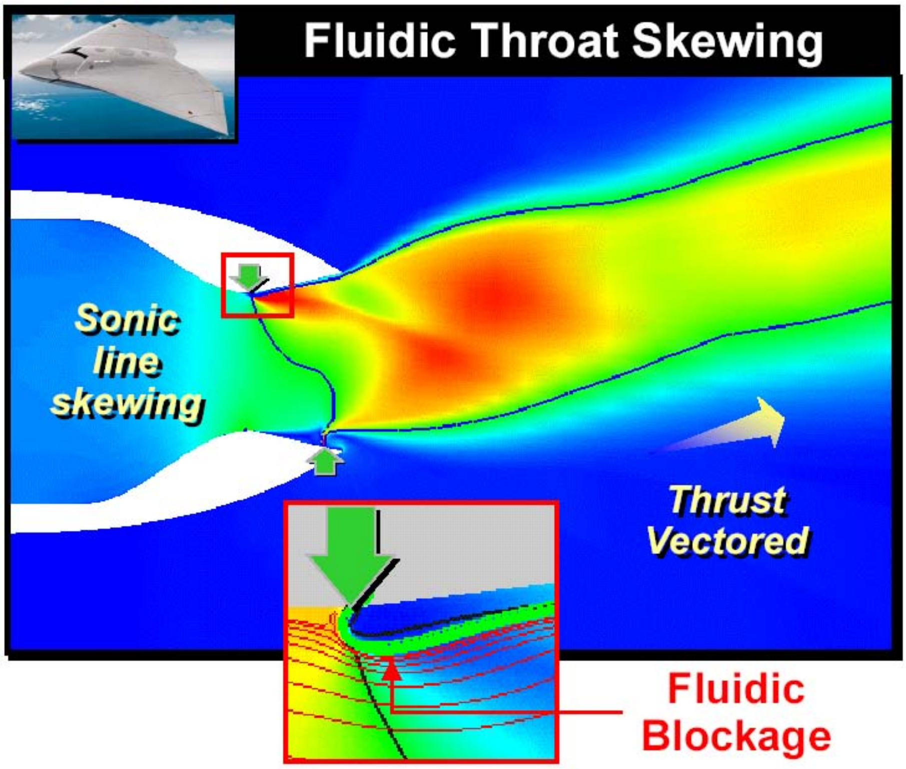

Figure 10. Thrust Vectoring Achieved Through Pulsed Injection

3.3 Fin Buffet Loads

Perhaps the most significant effort in characterizing the effects of unsteady aerodynamics on flight loads within the last 25 years, fin buffet consideration in design and operation of flight vehicles has been a major thrust at LM Aero. Through this consideration, several approaches have evolved which tackle the interaction of buffeting flows with the vehicle structure. These methods can be classified into two groups: open loop methods and closed loop methods. Open loop methods consider only the effect of the aerodynamic environment on the structures, and are used primarily in situations where the structurally induced flow angularity is much less than that of the dominate features in the flow-field. Closed loop methods allow the structural response to influence the aerodynamic predictions, and are primarily reserved for problems where this interaction plays a critical role. Wind tunnel and flight testing are also heavily relied upon in the characterization of buffeting loads (Reference 25).

Open loop methodologies have typically been applied with unsteady pressure data obtained through wind tunnel testing or CFD. There are currently two forms of the open loop methodology in use. The first solves the equations of motions in the frequency domain, and applies the buffeting loads in the form of a transfer function. (Reference 26) The second approach operates in the time domain, and makes use of RMS pressure distributions applied to structural modes, generalized masses and frequencies. Recent applications include analysis of F-16 ventral fin damage due to LANTIRN pod wake buffet, as shown in Figure 11, and F/A-22 Vertical Tail buffet. The time history approach, which utilized unsteady pressures obtained from wind tunnel testing, showed excellent agreement with flight test data when applied to the F-16 ventral fin buffet problem. Both open loop methods were applied to F/A-22 vertical fin buffet, using CFD generated data, and also showed excellent correlation with flight test data.

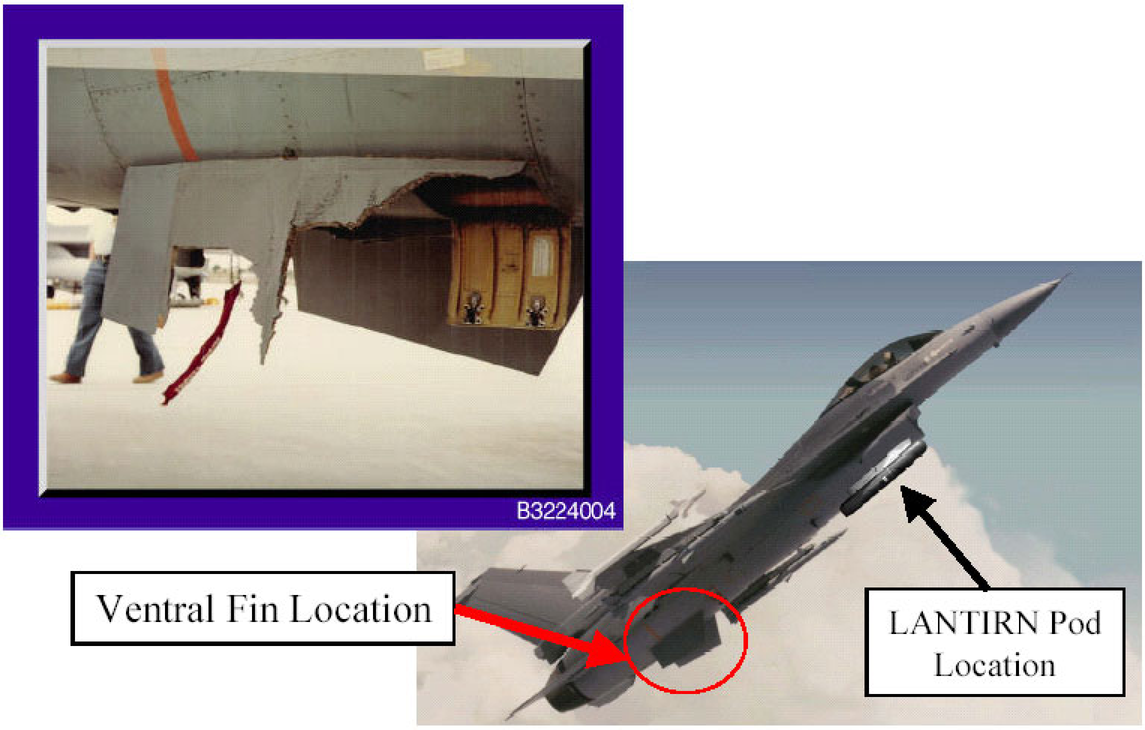

Figure 11. Ventral Fin Damage resulting from Interaction with LANTIRN Pod Wake

Closed loop methodologies, though simpler in concept, tend to be more difficult to implement due to the complexity of modeling the interaction between the aerodynamic and structural disciplines. The methods usually take the form of rigorously defined, fully coupled CFD / Finite Element Model or structural modal

analysis approach. LM Aero has applied this approach extensively to solve static aeroelasticity problems, as well as limited applications involving classical flutter, however this capability is still evolving to meet the demands of buffet problems. A fully coupled version of the time history approach described above has been applied successfully to F-16 ventral fin buffet. (Reference 27)

4.0 CURRENT WORK

4.1 Computational Aeroservoelastic Maneuver Simulation Environment

Lockheed Martin Aeronautics is currently developing a generic flight control system (GFCS) module for MDICE which will expand its computational aeroelastic environment into a maneuver simulation environment (depicted in Figure 12). Under U.S. Air Force sponsorship, this environment utilizes CFD to formulate a 1st order Taylor series approximation utilized by the GFCS for a closed loop trim of the aircraft, and uses a traditional time-marching scheme for a closed loop maneuver simulation.

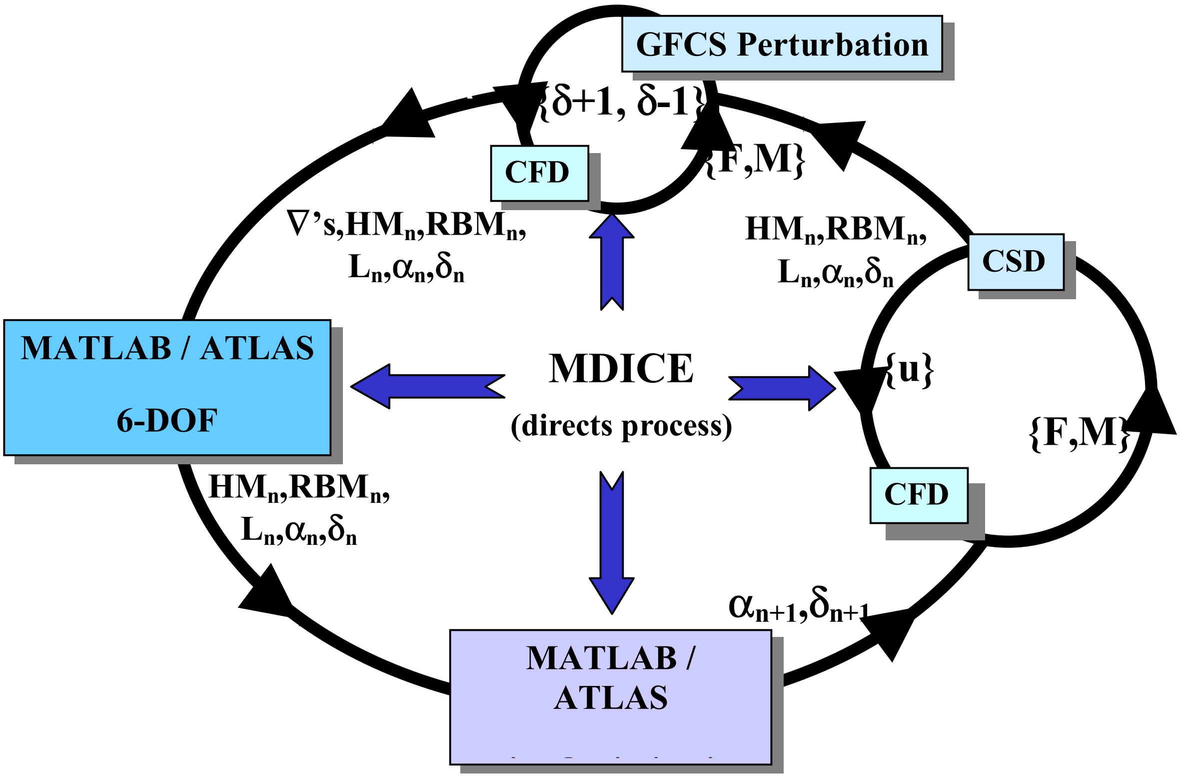

Figure 12. Aeroservoelastic Environment Implemented in MDICE

Modifications to the basic computational aeroelastic environment include accommodation of velocity computations for six degree of freedom motion and integration of flight controls modules. The Splitflow code has been modified with an arbitrary Lagrangian/Eulerian scheme to accommodate an accelerating reference frame describing a maneuver. Two flight control modules have been integrated into the MDICE process; ATLAS (Lockheed Martin Aeronautics legacy code) and MATLAB/Simulink™. Implementation of these codes is similar to that of Splitflow and other in-house written codes, where MDICE is provided control of execution and data is passed through pointers in memory. Code development, unit testing, and process integration are complete.

Two primary research issues not being addressed in this program are drag and propulsion integration. While the computation and application of drag in a computational aeroelastic solution is mechanically accommodated, the computational expense of viscous solutions in this environment is not acceptable. The accommodation and modeling of customer engine decks and appropriate engine interface boundary conditions in propulsion integration is a tedious and custom implementation that remains for future work. For six degree of freedom solutions, the flight controls aerodynamic database utilizes existing engine and drag performance data together with the CFD data. Thrust is considered to be a constant during the maneuver for the immediate future and is modeled in the CFD model to assure flow quality at desired solution points.

Application studies are currently being performed. To facilitate integrated testing, a three dimensional panel capability, QUADPAN, was implemented. Figures 13, 14, and 15 illustrate the models and results of integrated tests using linear panel model data. In these early studies, tolerance criteria for assessing trim has to loosened from traditional flight simulation experience due to the degree of nonlinearity in the overall aircraft forces and moments as functions of computational inherencies. It is anticipated that unsteady flows will add to the degree of difficulty in ascertaining trim. However, a time-accurate closed loop simulation should accommodate more readily.

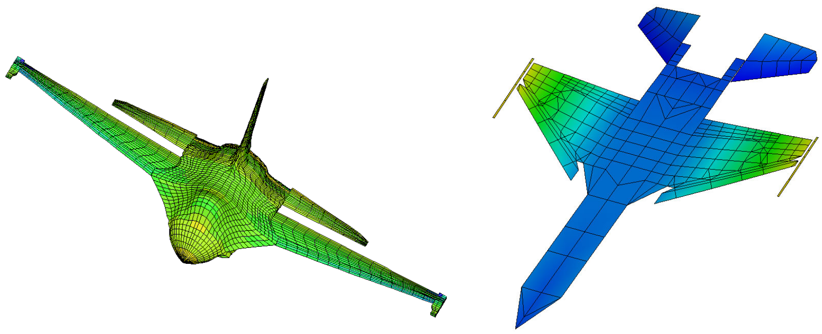

Figure 13. Aerodynamic and Structural Models used to Generate Trim Solution with ATLAS

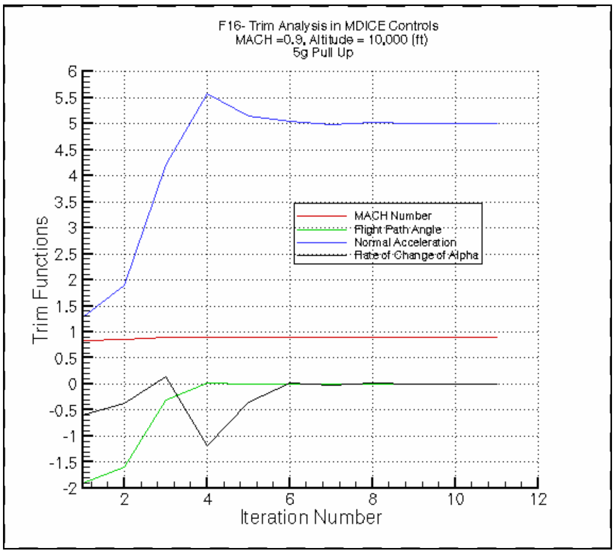

Figure 14. Static Trim Utilizing MDICE, ATLAS, Quadpan, and a Structural Modal Analysis.

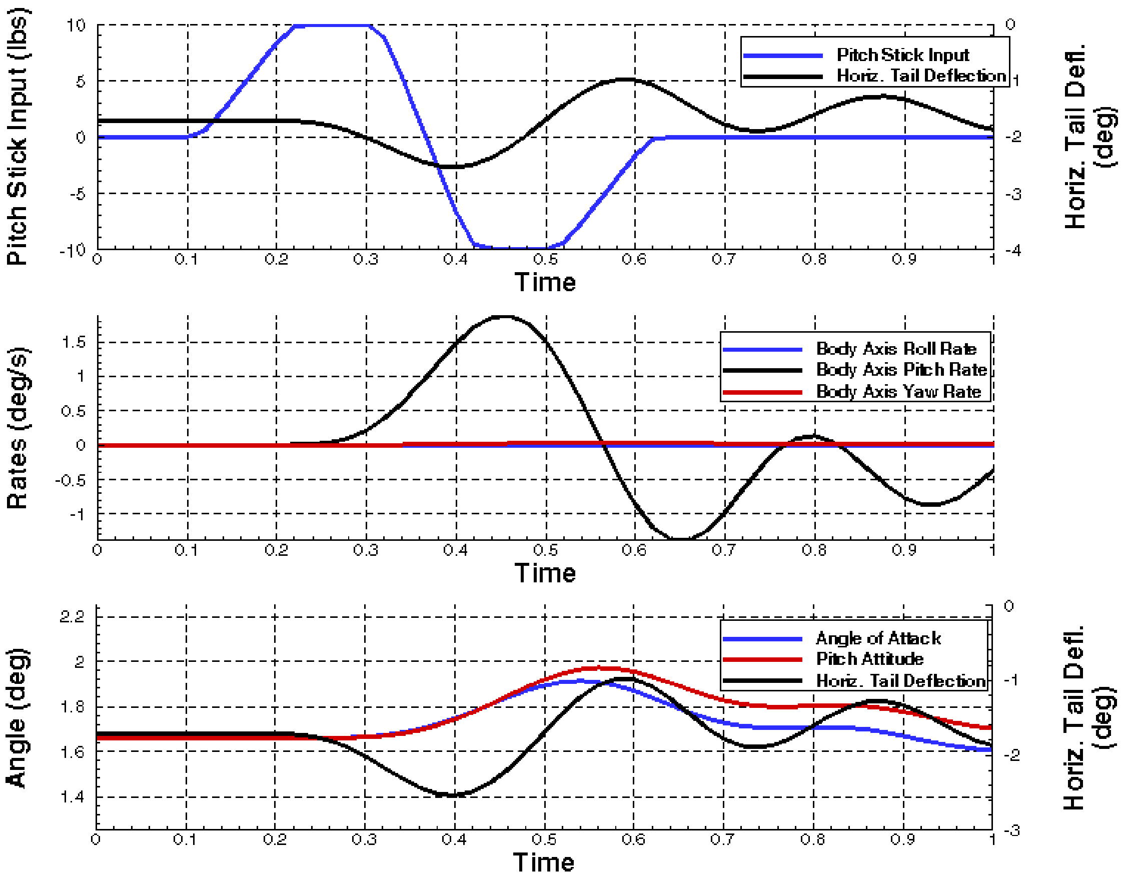

Figure 15. F-16 Maneuver Simulation in Computational Aeroservoelastic Environment, Utilizing MDICE, ATLAS, Quadpan, and a Structural Modal Analysis.

5.0 CONCLUDING REMARKS

This paper has provided an overview of CFD and unsteady loads experience at Lockheed Martin Aeronautics Company. It is a survey of work performed using rigid CFD to compute unsteady loads and aimed at incorporating CFD into a computational aeroservoelastic environment. This is an intentional and evolving effort that is balanced in building block validation, application based learning, and a vision for direct implementation. The vision is based on historical studies of "missed" critical loads where the dominant cause in events recorded is characterization of the aerodynamic flows.

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SYMPOSIA DISCUSSION

REFERENCE AND/OR TITLE OF THE PAPER: Keynote Address #4

DISCUSSOR'S NAME: M. Mendenhall
AUTHOR'S NAME: M. Love

QUESTION:
1. What is your experience with the state of the art in turbulence modeling for wakes?
2. How much of F-16 was required in modeling the design conformed fuel tank?

AUTHOR'S REPLY:
1. My particular experience is limited. Lockheed Martin's experience is extensive. There are references in my paper that are indicative. Modeling with RANS, URANS, and LES is available and has been used extensively. However I would refer people to my references for more information.
2. The entire airframe was modeled for design of the conformal fuel tank, while a reduced topology is used for the details of the gun blast wave.

DISCUSSOR'S NAME: T. Noll
AUTHOR'S NAME: M. Love

QUESTION:
1. What were the circumstances of not believing in wind tunnel test data references in the talk?
2. One of the objections of the Aero-Structural-Control working group was to eliminate transonic aeroelastic wind tunnel testing, what is the status of reaching that goal?

AUTHOR'S REPLY:
1. Sometimes test data show subtle behavior differences from one condition to another, such as a change in a stability curve (integrated result). I believe this was such a case. A high fidelity analysis coupled with the test would have led to an understanding and acceptance of the test data. In the case identified, the subtlety was disregarded and 'rediscovered' in flight.
2. At one point in the Aero-Structural-Control working group, the statement of a goal was made to 'eliminate' Transonic Aeroelastic Wind Tunnel testing. The goal was adjusted to one of 'minimize transonic aeroelastic wind tunnel testing'. The goal was stated with a benefit of reducing costs for aircraft development. It motivates the development of computational aeroelastic analysis. The reality of the state of the computational aeroelastic methods is that transonic aeroelastic wind tunnel testing will be needed for a long time. However, as a tool to be used jointly with testing, computational aeroelastic modeling provides the ability to gain insight into test results and may reduce time on test for various phenomena while providing for time on test for other phenomena. In other words, the net time on test may be reduced; or remain the same with allowance for enhanced test objectives. In short, transonic aeroelastic wind tunnel testing will be needed for the foreseeable future.